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ELECTROMAGNETIC RAILGUN HYDROGEN PELLET INJECTOR — PROGRESS AND PROSPECT

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ABSTRACT

A two-stage, fuseless, plasma-arc-driven electromagnetic railgun system suitable for hydrogen pellet acceleration has been developed and successfully tested. The first stage is a combination of a hydrogen pellet generator and a gas gun, which is responsible for injecting a medium-velocity hydrogen pellet into the second-stage railgun through a coupling piece. As the pellet enters the railgun, a specially designed arc-initiation scheme electrically breaks down the propellant gas which has followed the pellet from the gas gun into the railgun, thus forming a conducting plasma-arc armature immediately behind the pellet. This arc formation event coincides with the triggering of the main railgun current and allows the plasma-arc armature to subsequently propel the hydrogen pellet to a high velocity. Using this two-stage acceleration scheme with a 1-m-long railgun barrel, solid hydrogen pellet velocities in excess of 2.2 km/s have been achieved for a pellet 3.2 mm in diameter and 4 mm in length. The objectives of this paper are two-fold: first, a critical review of the achievements thus far on the railgun hydrogen-pellet injector and second, a description of the most recent technological developments and their implications for future work, in particular, the prospect of employing a railgun pellet injector for future large devices.

TWO-STAGE ELECTROMAGNETIC-RAILGUN HYDROGEN PELLET INJECTOR

Since its prototype version was first successfully tested for acceleration of a hydrogen pellet in 1985,[1,2] the two-stage, fuseless, plasma-arc-driven railgun system has gone through numerous improvements and design changes, not only to make it more reliable but to make it more suitable for high-current, high-voltage operation.[3-6] With the most recent system which has a 1-m-long railgun barrel and a 3.2-mm-diameter bore, the highest hydrogen pellet velocity achieved to date is in excess of 2.2 km/s. A general description of this system will first be presented. The arc-initiation scheme that ensures formation of a plasma-arc armature behind, not in front of, the pellet is the most critical element to the successful operation of a two-stage railgun system, and will be described in more detail. Hydrogen pellet acceleration results obtained most recently are then briefly reviewed. Based on the performance of the present system one can make predictions on the realistically possible hydrogen pellet velocities that may be achievable on an upgrade system. Such predictions are presented at the end as part of the concluding statements.

I. GENERAL DESCRIPTION

A schematic of the two-stage railgun system including the first-stage hydrogen pellet generator, the second-stage railgun, a coupling piece in between, the arc-initiation circuitry, the pulse-shaping network for the main rail current and the principal diagnostics is shown in Fig. 1. The hydrogen pellet generator serves a dual function: it fabricates a solid hydrogen pellet and injects it into the railgun through a coupling piece. The coupling piece helps form an uninterrupted pellet pathway from the gas gun to the railgun, but, more importantly, it serves as a pressure-relieving mechanism for the high-pressure propellant gas so that it does not follow the pellet into the railgun. By adjusting the number of perforations in the coupling piece, the amount of gas that can leak into the vacuum chamber that houses the coupling piece can be controlled. As a result, the pressure profile inside the railgun bore can be controlled so as to suppress spurious arcing during the railgun operation. The diagnostics are to measure the pellet velocities at the railgun breech and muzzle, to monitor the temporal behavior of the plasma-arc armature (and therefore the pellet in front of it) inside the railgun, to determine the pellet integrity and momentum, and to detect the currents through a few important circuits.

II. ARC-INITIATION SCHEME

The arc-initiation scheme that is responsible for creating a plasma-arc armature immediately behind the pellet is effected by a one-stage pulse-shaping network whose one end is a sharp tungsten needle mounted just inside the railgun at the breech. The pulse-shaping network is capable of delivering 315 A at 5 kV for a FWHM pulse width of 6 μS, and produces a very localized, high-charge-density plasma right behind the pellet. The idea is to create a lower-resistance path behind the pellet than the region in front of it so that when voltage is applied to the rails, the plasma-arc armature will form in the low-resistance region behind the pellet. All this is necessary because, in general, the gas pressure behind the pellet is higher and thus farther from the Paschen minimum than the pressure in front of the pellet and, as a result, an electrical breakdown is more favored in front of the pellet, not behind it.

The scheme described above that ensures formation of a plasma-arc armature behind the pellet works very well at low voltages. However, as the voltage is increased (which is necessary to achieve higher current) above a certain threshold voltage, it eventually stops working since the effectiveness of the arc-initiation scheme continuously weakens as voltage increases whereas the tendency for natural breakdown in the region ahead of the pellet increases. For the 3.2-mm-diameter railgun this threshold voltage turned out to be approximately 4 kV when the propellant gas pressure at the gas gun was 800 psi.

To resolve this problem, and thereby to enable high-current operation of the railgun, a perforated coupling piece housed in a separate vacuum chamber was used to reduce the gas pressure behind the pellet so that natural breakdown is equally favorable everywhere inside the railgun prior to turning on the arc-initiation scheme. The size and number of the perforations were chosen to reduce the gas pressure behind the pellet to a desired level. Using the perforated coupling piece the railgun system could be operated, without incurring spurious arcing, at voltages and currents as high as 10 kV and 23.5 kA, respectively ----- an operating condition that will probably allow one to determine the critical railgun current over which solid hydrogen pellet may fracture due to its limited yield strength.

III. HYDROGEN PELLET ACCELERATION RESULTS AND PROJECTIONS FOR LONGER-RAILGUN SYSTEMS

Using the two-stage railgun system illustrated by Fig. 1, pellet acceleration studies have been performed on solid hydrogen pellets, 3.2 mm in diameter and 4 to 6 mm in length. Output pellet velocities in excess of 2.2 km/s were achieved using an effective railgun length of 1 m, at a helium propellant gas pressure of 800 psi and railgun currents as high as 18.8 kA. The highest acceleration recorded was 2.92 x 10^6 m/s^2. Presented in Fig. 2 is a set of hydrogen pellet acceleration data corresponding to a single experimental sequence in which the railgun current was raised from 9.4 to 18.8 kA while the current pulse length, and therefore the pellet acceleration time, was held at 438 µs. The vertical and horizontal axes, respectively, represent the pellet velocity increment and the railgun current. The scatter in the data is mainly due to the variations in the pellet size and in the initial distance between the pellet and the plasma-arc armature, which could not be controlled accurately. According to this plot it appears that there is a parabolic relationship between the velocity increase and the rail current.

Based on these experimental results one can make predictions on the performance of a railgun with a longer gun barrel under the similar operating conditions. The predictions are listed in Table I for railguns of different lengths. The empirical acceleration values used for the calculation are the average and highest-to-date (parenthesized) values, respectively. From Table I, it is seen that a hydrogen pellet velocity on the order of 4km/s will be possible using a 3-m-long railgun.

Since with railgun one has the advantage of being able to exert a uniform acceleration force to a pellet, it should be possible to achieve very high hydrogen pellet velocities without resorting to a sabot to protect the pellet. Another advantage of a railgun injector is its unique capability to serve as a booster-accelerator. Since plasma-arc-armature velocities higher than 14 km/s are routinely possible, it should be boon to attach a railgun to an existing pellet injector to further incease the output velocity. We are currently in the process of utilizing and exploring such advantages of a railgun to their fullest extent.

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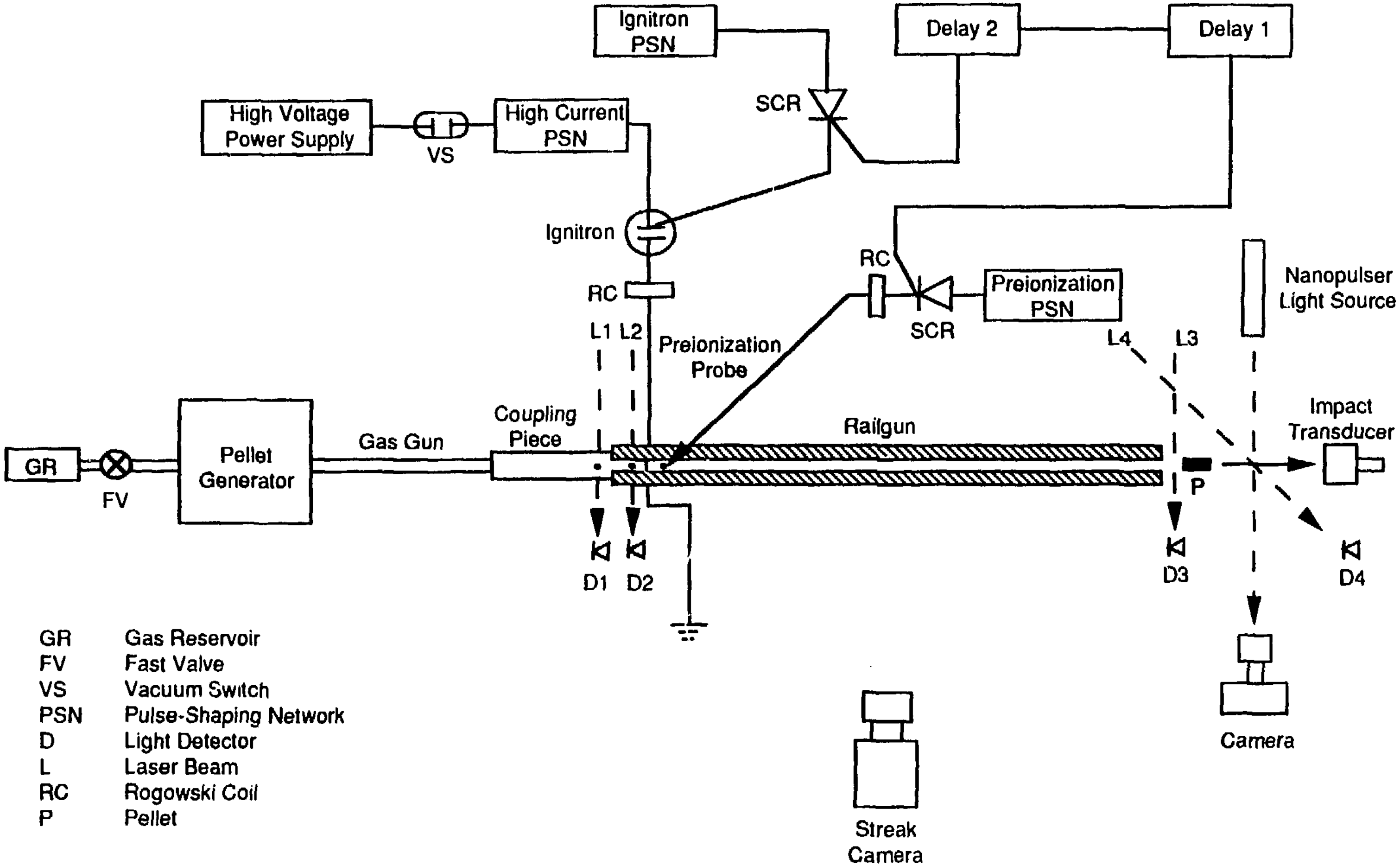

Figure 1. Schematic of the University of Illinois two-stage, fuseless, plasma-arc-driven railgun system with a pressure-relieving coupling piece

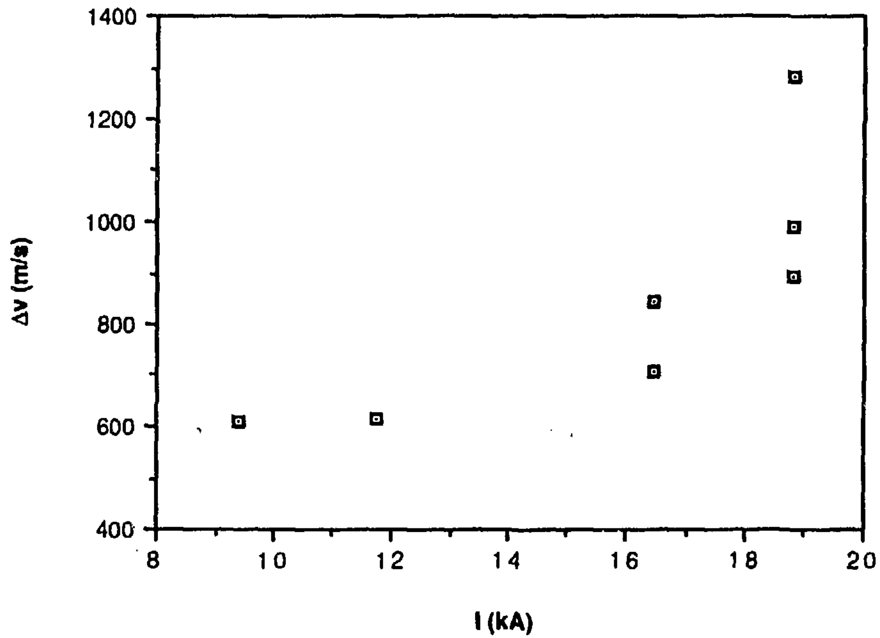

Figure 2. Increase in solid hydrogen pellet velocity plotted against railgun current. The solid hydrogen pellets were 3.2 mm in diameter and 4 to 6 mm in length and the pellet acceleration time on the railgun was 438 μs. The scatter in the data was due to the variations in the pellet size and in the initial distance between the pellet and the plasma-arc armature.

Table I. Predicted final velocities of a solid hydrogen pellet, 3.2 mm in diameter and 6 mm in length, accelerated by a 3.2-mm-diameter two-stage railgun of various lengths.

Parameter \ Length	2.0 M	3.0 M	4.0 M	5.0 M
v_{in}(m/s)	1000	1000	1000	1000
I (kA)	18.8	18.8	18.8	18.8
a (m/s^2)	2.00×10^6 (a) (2.92×10^6)(b)	2.00×10^6 (2.92×10^6)	2.00×10^6 (2.92×10^6)	2.00×10^6 (2.92×10^6)
v_{out}(km/s)	3.00 (3.56)	3.61 (4.30)	4.12 (4.94)	4.58 (5.50)
t (ms)	1.000 (0.877)	1.305 (1.130)	1.560 (1.350)	1.790 (1.541)
t_p (ms)	1.000	1.305	1.600	1.800
C_l (μF)	500 x 3	500 x 5	1000 x 5	1000 x 5
Z_o (Ω)	0.173	0.237	0.146	0.164
I/V (A/V)	2.35	2.11	3.43	3.05
V (kV)	8.00	8.91	5.47	6.16

t: pellet acceleration time
t_p: current pulse length

Note: Using a longer gas gun barrel and hydrogen gas as the propellant, higher input velocities (thus higher output velocities) should be possible.
(a) Average acceleration
(b) Best acceleration to date